

The Development of Climbing Mechanism for Cable Inspection Robot

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Abstract — For the maintenance of large cable-stayed bridge, cable inspection task using robot becomes an alternative method that is safer, easier and more efficient than a manual inspection. The method is believed to be superior than using drone or human in performing the cable inspection. Our research work focuses on the development of climbing mechanism for cable inspection robot. Our design of climbing mechanism enables the robot to climb on 115 mm cylindrical object, e.g. supporting cable or beam of the bridge. The mechanism can be controlled wirelessly to climb the cylindrical object with the diameter between 100 mm to 120 mm at maximum speed of 10 mm/s. The mechanism is powered by Li-Ion battery that is capable to reach 50 meter distance without the need of charging. The mechanism is also equipped with camera to take pictures of physical inspected objects, e.g. outer part of cable.

Index Terms— Climbing, Bridge Inspection, Robot, Mechanism.

I. INTRODUCTION

AS the main component of cable-stayed bridge load support, bridge cables greatly affect the serviceability, safety, and durability of the bridge as a whole. In the last ten to twenty years, High-Density Polyethylene (HDPE) has been adopted as the protection system for bridge cable [1]. HDPE has anti-corrosion properties, tough, hard, resistant to scratches, and also has good economic value. However, HDPE is susceptible to crack with age. Some of the factors causing cracks in HDPE include production defects, mounting errors, dynamic pressure, and environmental / weather factors. According to an international journal studying about bridge damage, 60% of damage ever to bridge cables is due to dynamic loads [2]. However, whatever the cause of the damage, once the crack reaches the cable core, the cable becomes susceptible to environmental corrosion [3].

Although HDPE coating technology continues to evolve, HDPE layer cracks can still occur [4]. This may lead to a more serious problem on the bridge cable, such as the appearance of rust spots, fatigue damage, and wear of cable core in a very short time [4]. Fatigue damage that accumulates can lead cable bridge structure to collapse. Fatigue damage has happened on the bridge structure of St. Nazaire in France in 2006 [5], the Kohlbrand Estuary Bridge bridge in Germany in 2006 [6], and the Luling bridge in the United States in 2010 [7]. These damaged bridge required the replacement of cables that cost more than half of the bridge's construction cost [4]. Worse yet,

fatigue damage has been resulting in an accident on the Haiyin Bridge in China (Fig.1). To prevent a similar case from happening again, periodic inspection are required to examine the cable lifetime.

Cable bridge structures are generally inspected periodically by professional workers with the use of hydraulic lift or a hanging lift (figure 1.2) [4]. This inspection method enables high accuracy of inspection (enables direct measurement of cracks), allowing inspection by multiple methods, while allowing minor improvements (such as bird nest removal or repainting of the cable protective coating). However, manual



Fig 1. Cable damage in Haiyin Bridge [4].



Fig 2. Cable inspection with hanging lift.

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inspection is inefficient and may endanger the safety of inspection workers. Using manual methods, an inspection team can only inspect an average of two cables per day because the preparation for inspection is time-consuming [4]. On the other hand, the advancement of robotic technology has enabled the realization of safer bridge cable structure inspection, easier to operate (does not require long preparation time) and is cheaper than manual inspection.

Drone is one of many robots that have the potential to be used for bridge cable inspection. Drones can be operated with just one worker, drones can also carry visual inspection devices (cameras), do not require long preparation, and can inspect many cables at once quickly. However, drones are not easy to be safely controlled along and around the cable, especially for close range inspection or high accuracy. In addition, the consumption of energy to fly drones is very high, lacking the ability to lift heavy loads, expensive, and limited inspection method, ie can only use inspection methods that do not require the operation from close range.

To answer the need for inspection methods a moving robot that can move on a 115 mm diameter cylindrical beam is designed to inspect bridge construction cables..

II. ROBOT DESIGN

The first prototype of a moving robot on a 115 mm diameter cylindrical beam is designed to have the climbing function, as well as carrying inspection device. The application of this robot as a bridge cable inspector is intended to be able to replace human work and as a better inspection solution than using drones to inspect the cable bridge efficiently. Pros (+) and cons (-) of the best possible methods for inspection, mainly by manual and drone, are analyzed as follows (Table 1) :

TABLE I
PROS AND CONS OF CABLE INSPECTION METHODS

| Manual Inspection |
|--|
| (+) Close range inspection. (+) Multiple inspection methods possibility. (-) Requires high operating costs. (-) Requires long preparation time. |
| Drone Inspection |
| (+) Can be used to replace human worker, thus reducing the risk of work accident. (+) Low operating costs. (+) Short preparation time. (-) Inspection using drones is not thorough and limited only to visual inspection methods. (-) Drones are not easy to control to inspect wires (-) Have a great risk of getting drone crashing on the bridge construction cable during inspection. |

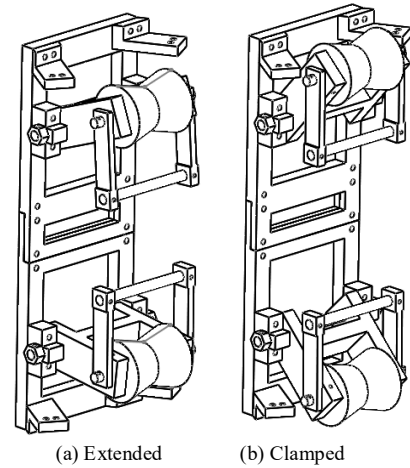


Fig 3. Clamp mechanism.

Considering the pros and cons of the two inspection methods mentioned in Table 1, a moving robot that can move on a 115 mm diameter cylindrical beam is designed with the specification as follows:

1. Low operation costs and low wasted energy
2. Easy and safe to be controlled to perform inspection.
3. Allow close range inspection.
4. Can be equipped with various inspection tools.
5. Does not take long to prepare and install on cable.

Robot is designed into several major components, namely : Frame, Clamp Mechanism, .

A. Frame

The robot frame is designed to form a hexagon. The frame consists of three bodies and six connecting rods. Each side of the hexagon is made separately, so only one side or one connecting rod needs to be unplugged when installing the robot on the cable. Each side is inserted using bolts and nuts. The robot frame was formed using 3D Printer with Polylactic Acid (PLA) plastic material. By using PLA plastics, the framework is more practical for manufacturing because the design can be directly realized by 3d printing.

B. Clamp Mechanism

Clamps are created to generate grips on the cylindrical rods, thereby allowing the movement of climbing rods. The clamp consists of swinging arms, springs, and wheels. The robot is designed to use two clamps mounted on two bodies, leaving only one body not paired with clamp. The spring is paired between the upper clamp arm and the lower clamp arm as a gripper. Clamp mechanism can be seen in Fig. 3. The extended position indicates that the arm is in a high tension position, where the spring is being drawn to its maximum. In contrast, the clamped position indicates that the clamp is in a lower tension position (minimal spring pull). Extended position will occur when the cylindrical beam diameter through which a large robot passes or the robot is being mounted on the rod. On the other hand, the clamped position will occur when the

cylindrical beam diameter being traversed in is small or medium sized.

In this design, the clamp force of each clamp mechanism is generated by one spring with a value of $k = 1.513 \text{ N/mm}$. The spring constant is obtained by testing under the Hooke's Law. The spring is given a load (m) of 1000 grams where g is the gravitational acceleration. The spring has a length of 100 mm without loading. After the load is given, the length of the spring changes to 106.48 mm. Thus, the change in length (x) is 6.48 mm. The spring constant is obtained by equation (1).

$$k = \frac{m \cdot g}{x} \quad (1)$$

Six wheels are attached to each arm, both clamped arm and non-clamped arm. The non-clamped arm is made rigid to produce a support reaction to the force coming from clamps. The wheels are used to produce linear motion on the cable. The wheels are formed with PLA plastic material and the surface is paired with double-tape to produce frictional force. Only one wheel paired with a double-tape is a drive wheel (motor-driven wheels). Passive wheels or wheels that are not motor-driven are not paired with double-tape. Both passive wheels and wheel drive, both are created to form the letter "V" with a slope angle of 150° (figure 2.2). The goal is to enlarge the wheel's contact area on the cable, so the grip and friction force on the cable is larger. The forces and reactions of the clamp mechanism are obtained through the sequential calculations. The top wheel of the robot is named sequentially as wheels 1, 2, and 3. While the wheels on the bottom are named as wheels 4, 5, and 6. The wheels are shaped V, so there are 2 center styles on 1 wheel. The wheel force resultant of N_i is formulated in equation (2) :

$$N_i = (N_{i1} + N_{i2}) \cdot \sin(0.5\beta) \quad (2)$$

$$F_{fi} = N_i \cdot \mu \quad (3)$$

The direction of the normal force N_i is perpendicular to the angle of the wheel. β is the angle of the wheel. The left tilt angle of the wheel and the right wheel is assumed to be symmetrical. The friction force F_{fi} of the i -th wheel can be calculated by equation (3).

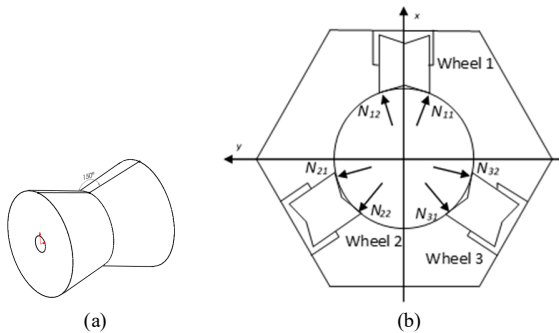


Fig 4. (a) Wheel, (b) Configuration of climbing wheel

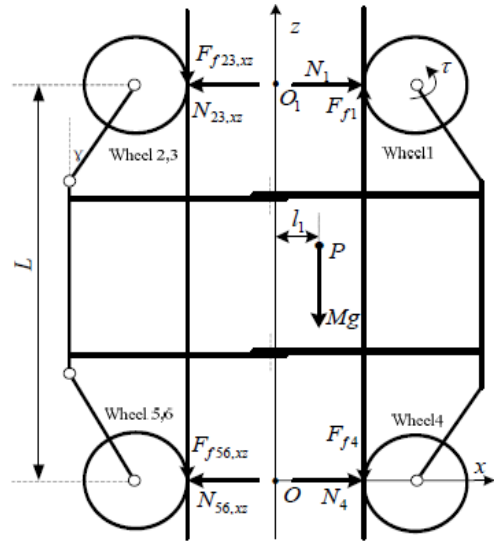


Fig 5. Free body diagram of forces working on XZ plane.

where μ is the coefficient of friction of the wheel when moving. Since the wheels are three pairs and not on the same plane, the calculation will be done by simplifying the N_i component into the XZ and YZ planes. Based on Figure 5, $F_{f23,xz}$ is the resultant frictional force of wheel 2 and wheel 3, $N_{23,xz}$ is the resultant force of wheel 2 and wheel 3. $F_{f56,xz}$ and $N_{56,xz}$ can be determined in the same way. All forces are equilibrium, based on the coordinates of the XZ plane (Fig. 5) the force equations in x direction coordinates is formulated in equation (4).

$$\Sigma F_x = N_1 + N_4 - N_{23,xz} - N_{56,xz} = 0 \quad (4)$$

$N_{23,xz}$ and $N_{56,xz}$ are simplified into N_2 and N_5

$$N_1 + N_4 - N_2 - N_5 = 0 \quad (5)$$

$$F_{f1} = \Sigma F_z + m \cdot g + F_{f2} + F_{f3} + F_{f4} + F_{f5} + F_{f6} \quad (6)$$

C. Moving Mechanism

The actuation mechanism the robot prototype is designed to comprise of two main components, the wheel and the DC motor. The drive wheel is driven using a DC motor. DC motors are used to convert DC electrical energy from batteries into kinetic energy to drive robots along wires. The DC motor is chosen according to the amount of torque required to lift the robot to climb the cable. In general, DC motors have high rpm and low torque. To increase torque, a gearbox is used. The amount of torque required to drive the robot is obtained through the following calculations:

Using the equation (7), the required DC motor torque was found to be 1.76 Nm .

$$\tau = r_1 (m \cdot g + 4\mu_1 N_{21} + 4\mu_1 N_{51} + 2\mu_1 N_{41}) \quad (7)$$

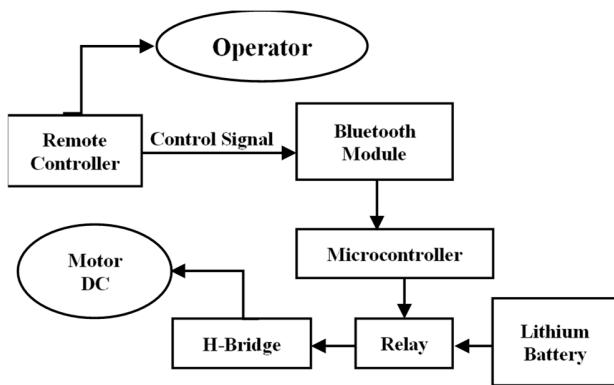


Fig 6. Block diagram of control system

Only one DC motor is used, which is installed only on the driving wheel. The location of the drive wheel is on the top of the robot.

Large torque motor is selected, so that when the load increases, the motor can still lift the robot. The motor is paired in a rectangular shaft and uses a wheel with a rectangular hole. At the other end there is also a bearing to smooth the rotation and preventing the rotation force damaging the wheel frame. If the radius of the wheel used is 2.91 cm, it can be calculated that the robot translation speed is 12 mm/s.

D. Control System

The control system is used to control the movement of the robot. Moving up and down motions are controlled according to the operator command. Robot control system is made possible by using Arduino UNO microcontroller with supporting components such as bluetooth module, relay, battery, H-Bridge module, and remote control. The block diagram of the control is shown in figure (6). Battery is the source of electrical energy used to drive a DC motor and to power the control and inspection system. The batteries type used are six cells of Lithium-Ion 3.7V - 4.2V (average 4V) arranged and connected in series, so the voltage reaches 22.2V-25.2V or 24V on average. The amount of power used in this first prototype to generate the drive system and the control system is shown in Table 2.

TABLE II
ELECTRICAL PROPERTIES OF SYSTEM

| Components | Voltage (V) | Current (A) | Power (Watt) |
|----------------|-------------|-------------|--------------|
| DC Motor | 1.0 | 2.0 | 3.0 |
| Control System | 5.0 | 6.0 | 7.0 |

Table 2.2. Battery specification

| Specification | Value | Unit |
|---------------|-------|---------|
| Voltage | 24 | DC Volt |
| Capacity | 2200 | mAh |

With the battery of 24 volt and capacity of 2200 mAh, the robot can operate within 3 hours and 36 minutes. If 14.36 Watt can drive a robot at 12 mm/s, then with a capacity of 2200 mAh battery, the robot can move as far as 155 m.

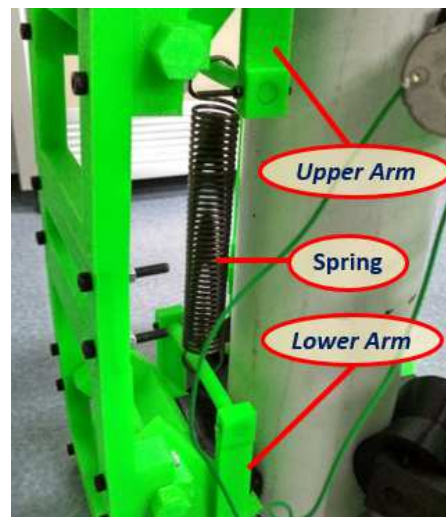
III. PROTOTYPE AND EXPERIMENTS

A. Climbing Mechanism Prototype

The design of mechanism including the control system has been realized into a prototype. The pictures of prototype can be seen in figure (7). The body of mechanism was built from PLA material using 3D printer. Due to limitation of the size that can be printed in 3D printer, the components were divided into links and joined with bolt and nut. The wheels are also made from PLA material and enclosed with rubber strip on the surface. The PLA material were considered adequate since it has good trade-off between stiff and elastic properties.



(a)

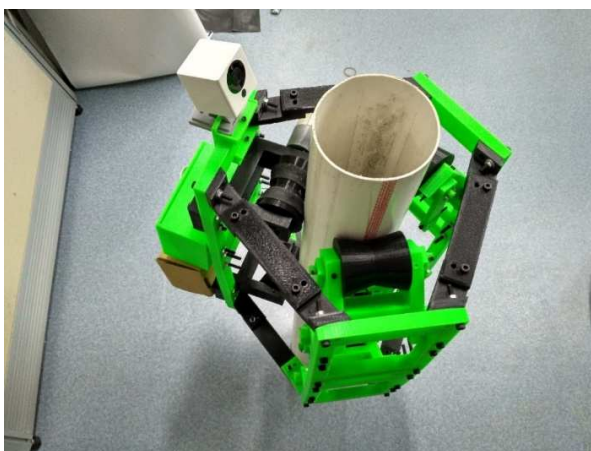


(b)

Fig 7. (a) Whole body of prototype (b) Clamping mechanism



(a)



(b)

Fig 8. (a) The mechanism clamped the dummy cable, (b) Camera for inspection is installed in robot

B. Experiment

In order to characterize the prototype, experiment has been conducted to know the maximum velocity, range, quality of the recorded image. The experiments were using a pvc pipe with diameter of 115 mm and 0.5 m length. The pipe was the dummy of bridge cable or beam (Figure 8). The experiment we conducted was considered as pre-eliminary study on the suggested mechanism. The experiment did not use real length of cable as used in general cable-stay bridge. However, in our opinion, the experiment has successfully evaluated the essential evaluation of climbing mechanism for inspection robot. The robot climbing mechanism was installed manually by inserting the pipe in the middle space of clamping component. The clamping component can be expanded since it uses several springs to adjust the middle circular area. After the mechanism has clamped the pipe, the mechanism was driven wirelessly by bluetooth connection. An app installed on smartphone with Android Operating System was the controller to move the mechanism up and down.



Fig 9. Captured inspection image from camera

IV. RESULT AND DISCUSSION

Based on the experiment, the time required to travel 0.5 meters of cable is 25.4 seconds. This means that the robot can move at a speed of 1.96 cm / sec. With such speed, the robot prototype can travel a distance of 50 meters in 2551 seconds or 42 minutes. In addition, the robot is also tested to perform remote inspection. The robot has been tested and the result of the robot can send remote inspection results to the operator monitor screen. Results of inspection images obtained can be seen in Figure 9.

V. CONCLUSION

The design of climbing mechanism for cable inspection robot has been proposed. The prototype has been build and tested in an experiment. The mechanism can climbed the dummy object of bridge cable while being wirelessly controlled. From the experiment it can be found that the maximum speed of the robot was 1.96 cm / sec that can perform 50 meters cable inspection within 42 minutes. The robot was able to capture the inspection image using camera. While there are still space for improvement in future version, the climbing mechanism can initiate advancement in the field of cable inspection using robot.

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